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Searching for Primordial Black Holes in the radio and X-ray sky

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We model the accretion of gas on to a population of massive primordial black holes in the Milky Way, and compare the predicted radio and X-ray emission with observational data. We show that under conservative assumptions on the accretion process, the possibility that $\mathcal{O}(10)\,M_\odot$ primordial black holes can account for all of the dark matter in the Milky Way is excluded at 4σ by a comparison with the VLA radio catalog at 1.4 GHz, and at more than 5σ by a comparison with the NuSTAR X-ray catalog ($10-40$ keV). We also propose a new strategy to identify such a population of primordial black holes with more sensitive future radio and X-ray surveys.

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Introduction: The first direct detection of a gravitational wave signal, announced by the LIGO collaboration earlier this year [1] demonstrated the existence of $\sim 30 M_\odot$ black holes (BHs), prompting the suggestion [2] that these objects are *primordial* black holes (PBHs) that may account for all of the dark matter (DM) [3–5] in the Universe. The connection between PBHs and DM has been extensively studied in the past (see e.g. [6–11]), and a number of constraints exist on the cosmic abundance of PBHs over a very wide mass range (see the discussion below, and e.g. Ref. [12] for a recent review).

In this Letter we study the X-ray and radio emission produced by the accretion of interstellar gas on to a population of $\mathcal{O}(10)\,M_\odot$ PBHs in the Milky Way, focusing in particular on the inner Galaxy. Given current estimates of the bulge mass [13], if PBHs constitute all of the DM, there should be $\mathcal{O}(10^9)$ such objects within 2 kpc from the Galactic center (GC). Since the inner part of the bulge contains high gas density [14], a significant fraction would inevitably form an accretion disk and emit a broad-band spectrum of radiation. We show (fig. 1) that radio and X-ray data in the Galactic Ridge region rule out, at 4 and 10σ respectively, the possibility that PBHs constitute all of the DM in the Galaxy, even under conservative assumptions on the physics of accretion.

Our limits arise from a realistic modeling of the accretion process, based on the observational evidence for inefficient accretion in the Milky Way today [15, 16], and corroborate, with a completely independent approach, the exclusion of intermediate-mass PBHs as DM candidates.

Accretion on black holes: For PBHs in the Galactic bulge, the accretion rate $\dot{M}$ is well below the Eddington limit $\dot{M}_{\rm Edd}$. Even under the unrealistic assumption of Bondi-Hoyle-Lyttleton accretion [17, 18], and typical velocities as low as ~ 10 km/s, the accretion rate would definitely be sub-Eddington $\dot{M} \sim 10^{-5}\left(n_{\rm gas}/{\rm cm}^{-3}\right)\dot{M}_{\rm Edd}$.

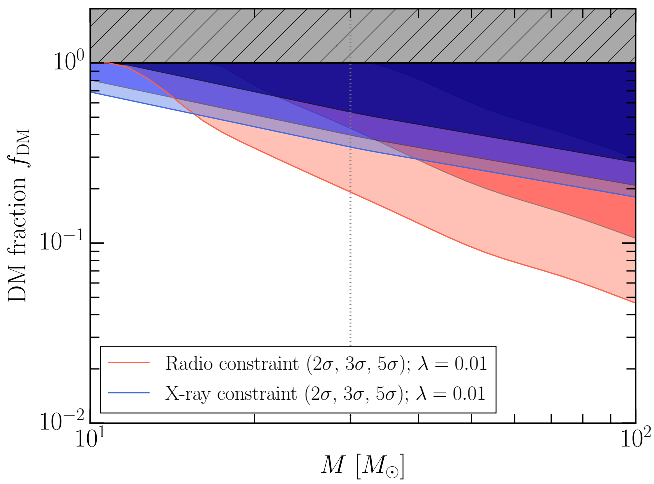

FIG. 1. Upper limits on the fraction of DM in PBHs of a given mass M, arising from the non observation of bright X-ray (blue shaded regions) and radio (red) BHs candidates at the GC. We assume a conservative value of the parameter λ regulating the departure from Bondi accretion rate, $\lambda = 0.01$. The dotted grey line corresponds to $30 M_\odot$ PBH, while the hatched grey region is unphysical ($f_{\rm DM} > 1$).

BHs accreting at $\dot{M} < 0.01\ \dot{M}_{\rm Edd}$ are radiatively inefficient, such that the luminosity scales non-linearly with $\dot{M}$ [19]. The prevailing physical pictures adopted to explain the weak emission properties are advection-dominated accretion in which the gas cooling timescales greatly exceed the dynamical timescales [20], and mass loss from the disc or internal convective flows, such that the accretion rate itself has decreased once gas reaches the inner edge of the disc [21, 22]. It is likely that both mechanisms are at play, a view supported by both radio and X-ray constraints on the gas density around Sgr A*, the supermassive BH at the center of the Galaxy, the least luminous accreting BH observed to date (in Eddingtion units), and thus a well-studied source from the point of view of weak accretion physics [23–25]. We compute the accretion rate and the radiative efficiency in the low-efficiency limit, following the formalism presented in [26].

We model the radiative efficiency η, defined by the relation for the bolometric luminosity $L_B = \eta \dot{M} c^2$, as $\eta = 0.1 \dot{M}/\dot{M}_{\rm crit}$ for $\dot{M} < \dot{M}_{\rm crit}$ (if we were to assume instead efficient accretion above the critical rate, $\dot{M} > \dot{M}_{\rm crit}$, then we would have a constant $\eta = 0.1$). As already discussed, all our sources fall below this critical accretion rate, such that they are all inefficient accretors: this means the luminosity scales non-linearly with accretion rate, $L \propto \dot{M}^2$.

We parameterise the accretion rate as $\dot{M} = \lambda \dot{M}_{\rm Bondi}$, with $\lambda \sim 0.01$ based on isolated neutron star population estimates and studies of active galactic nuclei accretion [15, 16, 25]. The accretion rate $\dot{M}$ is therefore given by

$$\dot{M} = 4\pi\lambda(GM_{BH})^2\rho\left(v_{BH}^2 + c_s^2\right)^{-3/2} \qquad (1)$$

where G is the gravitational constant, v_{BH} is the velocity of the BH, and c_s is the sound speed of the accreted gas, which is below 1 km/s in cold, dense environments. This prescription is the same as that adopted by [26]; however, we consider $M_{BH} = 30\ M_\odot$, and rescale the value of $\dot{M}_{\rm crit}$ used in that work across the full 10–100 $M_\odot$ mass range.

We convert bolometric luminosity to X-ray luminosity via the approximate factor $L_X \simeq 0.3\, L_B$ following [26].

Motivated by the results presented in [27] and by the discussion in [26], we assume the presence of a jet – thus requiring a system with a surplus of angular momentum – emitting radio waves in the GHz domain with an optically thick, almost flat spectrum, whilst the X-ray emission is non-thermally dominated, originating from optically thin regions closer to the BH. In order to convert the X-ray luminosity into a GHz radio flux, we adopt the universal empirical relation discussed e.g. in [28], also known as the *fundamental plane (FP)*, a solid empirical relation which applies for a remarkably large class of compact objects of different masses, from X-ray binary systems to active galactic nuclei. We take the X-ray luminosity in the 2–10 keV band (thus also allowing comparison with *Chandra* catalogues) in accordance with the FP, assuming a hard power-law X-ray spectrum with photon index α, and a typical range for hard state X-ray binaries of 1.6–2.0 (see [29]). We extrapolate this power-law spectrum into the 10–40 keV band in order to also make comparisons with NuSTAR catalogues. We then use the FP relation to calculate the 5 GHz radio flux from the 2–10 keV X-ray flux and assume a flat radio spectrum, such that $F_{5\,\rm GHz} = F_{1.4\,\rm GHz}$, allowing direct comparison with the 1.4 GHz source catalog from a VLA survey of the GC region.

Primordial black hole population: In order to derive a bound from X-ray and radio data, we set up a Montecarlo simulation for each PBH mass, assuming a delta mass function.

We populate the Galaxy with PBHs following the Navarro-Frenk-White (NFW) distribution [30] (other more conservative choices are discussed below). We implement the accurate 3D distribution of molecular, atomic, ionized gas in the inner bulge presented in [14]; that distribution includes a detailed model of the 3D structure of the Central Molecular Zone (CMZ), a 300 pc wide region characterized by large molecular gas density and centered on the GC, i.e. in the region where the largest density of PBHs is expected.

For each PBH, the velocity is drawn randomly from a Maxwell-Boltzmann distribution. The characteristic velocity of the distribution is position-dependent. The velocity distribution at a given radius is a crucial ingredient, because the accretion rate scales as v^{-3}, eq. (1). In order to derive such a distribution, we consider the recent state-of-the-art model for the mass distribution in the Milky Way described in [31], where 6 axis-symmetric components are taken into account (bulge, DM halo, thin and thick stellar discs, and HI and molecular gas discs). We then assume that the velocity distribution at a distance R from the GC is a Maxwell-Boltzmann with $v_{\rm mean} = v_{\rm circ}(R) = \sqrt{(G\,M(<R)/R)}$. Under the assumption of isotropic orbits[1], an exact computation of the phase-space density could be performed by means of the Eddington formalism [32], as done e.g. in [33]. We checked that our simple approach is equivalent in the low-velocity tail, up to $v \simeq 40$ km/s[2]. Since our results depend only on PBHs with velocities $\lesssim 10$ km/s (see below), we can safely neglect the high-velocity tail and adopt the simple formalism described above.

Given the mass, position and velocity of each PBH (and the gas density), we compute accretion rate, X-ray, and radio emission adopting the prescriptions discussed in the previous section.

Radio BH candidates: The 1.4 GHz source catalog from a VLA survey of the GC region [34] contains 170 sources in a $1^\circ \times 1^\circ$ region centered on the GC. The minimum detectable flux for this catalog is ~ 1 mJy. In order to compare our predictions to the observations, we carry out a data analysis on the VLA catalog and check if there can be any BH candidate among the detected sources. If any of these sources are accreting BHs, their X-ray and radio emissions should be co-located. We therefore compare the radio catalog with the X-ray point

[1] We verified that, in the high-resolution Aquarius N-body simulations, the anisotropy parameter $\beta = 1 - \sigma_t/\sigma_r$ is consistent with 0 in the whole range of radii we are interested in, therefore the assumption of isotropic orbits is solid.

[2] M. Fornasa, private communication.

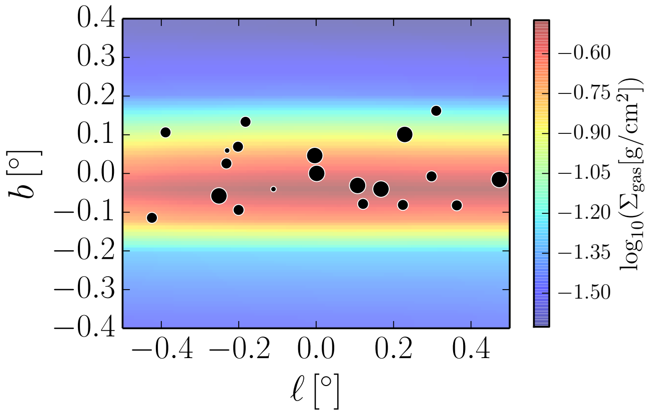

FIG. 2. Example of the distribution of PBHs detectable by VLA in the ROI, for one Montecarlo realisation. The colored background depicts the column gas density. The size of the black points is proportional to the PBH velocity in the range 0.3 − 3 km/s (for detectable PBHs).

source catalog from [35], which contains 9017 sources detected by *Chandra* in the $0.5-8$ keV band in a $2° \times 0.8°$ band centered on the GC, and search for all sources in both catalogs that have positions within $10''$ of each other.[3]

We find 24 sources in both the X-ray and radio catalogs within $10''$ of each other. If we assume these sources are accreting BHs, then their X-ray and radio fluxes should lie on the FP, as explained above. We therefore use the FP to predict the X-ray flux from the radio flux of each of these objects (24 in the very conservative case, 9 if we exclude likely foreground sources).

We find that the predicted X-ray fluxes are substantially larger ($\sim 3-7$ orders of magnitude) than the flux reported in the catalog from [35]. If we instead use the X-ray fluxes from the catalog to predict the radio fluxes, we find that the radio fluxes are correspondingly $3-7$ orders of magnitude below the detection threshold of the VLA survey in [34].

We therefore conclude that none of the 24 (or 9 likely Galactic) sources with overlapping positions lie on the FP, and therefore, given the assumptions described above regarding the presence of a jet, we have no BH candidate in our sample.

X-ray BH candidates: Hard X-ray emission ($>$ 10 keV) suffers from far less Galactic absorption than soft X-ray emission and is therefore a good band to search for emission from accreting BHs. We consider sources detected by the NuSTAR space telescope in the $10-40$ keV band [36] in a small region-of-interest (ROI) including the high-density region of the Galactic Ridge, $-0.9° < l < 0.3°$; $-0.1° < b < 0.4°$. NuSTAR detected here 70 hard X-ray sources [29]. All of these sources have counterparts in the *Chandra* source catalog [35]. We again search for overlapping positions between the NuSTAR sources and the VLA sources. We find zero sources in the NuSTAR catalog that are within $80''$ of a VLA source (the angular resolution of NuSTAR is $18''$). We therefore conclude, under the aforementioned assumptions, that none of the observed NuSTAR sources can be BHs. As an additional check, if we apply the FP to predict the 10–40 keV emission from the observed radio emission from all of the radio sources detected in the VLA catalog [37], we find that the luminosities of all 170 sources are $> 10^{35}$ erg s^{-1}. This is well above the detection threshold of 8×10^{32} erg s^{-1}, and implies that all 170 radio sources would have been easily detected by NuSTAR if they were accreting BHs.

Results: The main result of the Letter is presented in fig. 1. We display the 2σ, 3σ, and 5σ constraints on the DM fraction as a function of the PBH mass.

The upper limits are derived as follows. We perform $\mathcal{O}(100)$ Montecarlo simulations for 10 reference values of the mass in the $10-100\ M_\odot$ interval, assuming a DM fraction $f_{\rm DM} = 1$. We determine the mean and standard deviation of the distributions of the predicted number of PBHs with radio fluxes above the VLA threshold and with X-ray fluxes exceeding the NuSTAR threshold, in the corresponding ROIs. We verify that the number of bright PBHs is compatible with Poisson statistic and the average predicted number scales linearly with $f_{\rm DM}$. We derive the radio and X-ray bounds by comparing the number of predicted PBHs with the number of BH candidates derived from the analysis of radio and X-ray catalogs described in the previous section.

In fig. 2, we show the PBHs detectable by VLA at 1.4 GHz assuming a PBH mass of $30 M_\odot$ and DM fraction equal to 1, for one specific Montecarlo realisation. This scenario predicts, on average, 21 ± 5 sources above the VLA flux threshold and, thus, it is excluded by more than 4σ from radio observations. However, it is important to understand where the constraining power comes from: The PBHs above the detection threshold, and thus the ones with the larger X-ray flux, lie in the very inner region of the Galaxy where the column gas density is the highest and show very small velocities, in the range $\sim 0.3-3$ km/s. Therefore, the constraints arise from the very low velocity tail of the distribution and from regions correlated with very high column densities, e.g. CMZ, as already mentioned above.

Discussion and conclusions: In this Letter we derive new, strong constraints on the hypothesis that PBHs

[3] This is a very conservative separation. The positional accuracy of *Chandra* is $< 1''$. For the VLA, the positional accuracy is typically a small fraction of the synthesized beam, $2''.4 \times 1''.3$ for the survey in [34]. A separation of $10''$ is chosen in [34] to search for positional coincidences in other radio catalogs; we therefore also adopt $10''$ as the maximum allowed separation.

make all of the DM in the Universe. In particular, we find that PBHs with $M \simeq 30 M_\odot$, that could be responsible for the gravitational waves detected by LIGO, contribute less than 20% to the whole DM density.

In the mass window $10 - 100\ M_\odot$, our constraints are competitive with (and even stronger than) those arising from the study of microlensing events with the MACHO project [38] (for $\gtrsim 15 M_\odot$) and than those from halo wide binaries [39, 40] (for $\gtrsim 60 M_\odot$). For $M \gtrsim 10 M_\odot$, they are also comparable or stronger than the constraints from the survival of central star clusters in faint dwarf galaxies, in particular in Eridanus II [41, 42]. Even more stringent constraints arise in principle from the analysis of the Cosmic Microwave Background (CMB) [43]. However, those arising from the analysis of spectral distortions (based on FIRAS data) turned out to be much weaker than originally thought [44], while the ones based on the study of CMB anisotropies (see also the recent results by [45]), are based on assumptions on the accretion of gas on PBHs in the early Universe that are still under debate, as the modelling of the accretion process is based on theoretical arguments, and not directly supported by observations as in our case (see also the discussion in [44]).

In contrast with [43], in fact, we adopt a very conservative prescription, compatible with current astronomical observations, for both the accretion rate and the radiative efficiency, setting the ratio of the actual accretion rate to the Bondi rate, λ, equal to 0.01. Moreover, we exploit for the first time in this context the empirical FP relation between radio and X-ray emission, which has been observed on a wide class of sources in a large mass range, from X-ray binaries to active galactic nuclei. Adopting such a relation, we are able to predict the radio and X-ray luminosity expected by a population of PBH in the Galaxy compatible with the DM phase-space distribution, as well as to look for BHs candidates in radio and X-ray catalogs. We set upper limits on the DM PBH fraction using both radio (VLA) and X-ray (NuSTAR) point-like source catalogs, by comparing the number of expected PBHs above threshold and the observed number of BH candidates in a very narrow region about the GC.

These bounds are robust with respect to the modeling of the full velocity distribution, since the predicted number of bright PBHs only depends on the very low-velocity tail (< 10 km/s) where we checked the agreement among different numerical/analytical methods. Moreover, our limits are independent of the details of the gas distribution (we checked that the bound is still present even with a naive modeling of the CMZ as a sphere with uniform density compatible with the mass constraints provided in [14]). They are also not affected significantly by a shallower DM profile as proposed e.g. in [46]; however, assuming an even flatter profile like the Burkert one (an extremely conservative assumption for our Galaxy), the bound is present only for $\lambda \gtrsim 0.2$.

We recall that our limits hold for a narrow mass function; a detailed study of the impact of different mass distributions is beyond the scope of the present paper and postponed to a future work.

Although our radio and X-ray bounds vanish for $\lambda \lesssim 2 \cdot 10^{-3}$, future instruments will be able to prove further the accretion model as well as the PBH DM fraction. We here briefly discuss prospects for radio observations. Given the significant increase in sensitivity of future radio telescopes, we expect an important part of the yet-allowed parameter space to be probed by upcoming facilities such as MeerKAT and, later, SKA. Using the radiometer equation [47], the minimum (1σ) detectable radio flux is $S_{\nu,\mathrm{rms}} = (T_{\mathrm{sky}} + T_{\mathrm{rx}})/(G\sqrt{2\,T_{\mathrm{obs}}\,\Delta\nu})$. For MeerKAT, we assume gain G = 2.9 K/Jy, receiver temperature $T_{\mathrm{rx}} = 25$ K, sky temperature towards the GC $T_{\mathrm{sky}} = 70$ K, and bandwidth $\Delta\nu = 1000$ MHz [48]. For one hour of observation time, the instrumental detection sensitivity of MeerKAT turns out to be ~ 0.01 mJy (significantly above the source confusion limit), which would give, on average, 88 ± 11 detectable PBHs, for $\lambda = 0.001$ and $M = 30 M_\odot$. Similarly, we can predict the number of PBHs above the MeerKAT source detection threshold, for a DM fraction still allowed by VLA ($f_{\mathrm{DM}}= 0.1$) – fixing $\lambda = 0.01$. In this case, the number of detectable $30 M_\odot$ PBHs will be on average 99 ± 9 (with velocities up to ~ 10 km/s), showing, also in this case, the power MeerKAT (and even more SKA) will have to either strengthen the bound or to detect a possible subdominant population of PBHs (although the exptected population of astrophysical BHs becomes comparable with the primordial one for DM fractions lower than $\sim 10^{-3}$).

Interestingly, our procedure can be applied also to the search for astrophysical BHs in the Galaxy, adopting the realistic spatial and velocity distributions expected for those objects. Our formalism has the potential to characterize this guaranteed population of objects in future analysis.

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